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Spatial and temporal monitoring of soil moisture using surface electrical resistivity tomography in Mediterranean soils

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ABSTRACTS

ERT techniques are especially promising in (semi-arid) areas with shallow and rocky soils where other methods fail to produce soil moisture maps and to obtain soil profile information. Electrical Resistivity Tomography (ERT) was performed in the Peyne catchment in southern France at four sites located on four different geological substrates. The main objective was to test the usefulness of such geoelectrical method for the assessment of spatial and temporal variability of soil water content and to demarcate subsurface horizontal zones: topsoil, active zone and bedrock. We used time lapse ERT to separate lithological variability from soil moisture content and to evaluate its potential to demarcate subsurface soil horizons. Three measurement campaigns were carried out and field data were collected using the Sting R1/IP advanced resistivity meter with one-channel receiver. We used an array of 28 electrodes with 1 m spacing, which provided reliable resistivity information to a depth of approximately 5.5 m. ERT were followed by soil sampling carried out with a hand auger, directly below the respective geoelectrical profiles. Empirical linear regression was used to determine the specific relationships between volumetric soil moisture of the field samples and electrical resistivity data obtained in situ. Our conclusions are that ERT is a useful technique for providing information on the spatial–temporal variability of water content in semi-arid areas and for reaching depths otherwise inaccessible. In this study we proposed a method to delineate three important different soil zones: topsoil, active zone, bedrock, based on resistivity data. These three layers are essential information in understanding and modelling the interaction between subsurface and vegetation water uptake, particularly in semi-arid regions.

1. Introduction

The climate in the Mediterranean regions -with long dry periods in summer, mild winters and concentrated rainfall events in spring and autumn- is an important control on vegetation growth, which is further influenced by the often marginal and degraded soil conditions. Regional climate change scenarios predict that the extreme character of the Mediterranean climate will increase: higher temperatures, longer periods of drought and more violent concentrated rainfall events (Gao and Giorgi, 2008). These changing environmental conditions will probably have a deteriorating impact on the Mediterranean ecosystems and landscapes. Annual average precipitation will not change much, but the distribution of precipitation over the year will shift to a stronger seasonal character with dryer summers and more humid winters and furthermore, a shift towards shorter and more intense rainfall events. For vegetation growth, these climate changes will cause decreased water availability during the summer growing season (Nijland, 2011). The dependence of vegetation on soil water storage will therefore increase.

Water availability is an important constraint on vegetation growth in arid and semi-arid regions. During prolonged periods of summer drought, water stored in the soil column is the only available water source for plants and trees. If the soil moisture content drops below a certain level, stomatal closure is induced to reduce water loss, prohibiting photosynthesis (Damesin and Rambal, 1995; Hoff et al., 2002). A drought-induced growth stop is common in Mediterranean regions and this limits ecosystem productivity. Water available in the soil for plants is a function of the precipitation, water retention capacity of the soil (pore space, effective depth or active zone), the root distribution of tree, shrubs and plants in the soil, and the ability of water to flow towards the roots i.e. water conductivity (Lambers et al., 1998). Mediterranean

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areas are especially difficult for plants due to the uneven distribution of precipitation in time (relative wet winters and dry summers) and shallow eroded soils (Driessen et al., 2001; Bonfils, 1993).

Information on soil water content and its spatial temporal distribution is crucial for studying primary productivity of these vegetation types and to assess by model simulations the impact of global change on the productivity, the health status and the composition of Mediterranean vegetation. We anticipate that the here proposed Electrical Resistivity Tomography (ERT) approach will yield quantitative information on soil moisture content and allow us to follow soil moisture content over time, and will furthermore provide us with information about the depth of the active zone where water is stored and where the majority of the roots extract plant water.

ERT is documented as a non-invasive geophysical soil survey and monitoring method. It has been used to delineate solute plumes (de Franco et al., 2009; Clement et al., 2010), monitor flow in the unsaturated zone (Barker and Moore, 1998; Binley et al., 2001; Arora and Ahmed, 2011), determine soil water deficit and plant available water (Brunet et al., 2010), study root distribution and root water uptake (Rossi et al., 2011; Srayeddin and Doussan, 2009), define horizon location and stratification (Vanwalleghem et al., 2010; Chaplot et al., 2010), observe soil water dynamics (Nijland et al., 2010; Amato et al., 2009) defining depth to bedrock (Coulouma et al., 2012; Shafique et al., 2011), and used to characterize active-layer depth, soil-moisture content, and permafrost variability (Hubbard et al., 2013).

The main aim of this study was to test the usefulness of the ERT method for the assessment of spatial and temporal variability of soil water content along the transects and to demarcate horizontal zones in the soil profile (top layer, active layer and bedrock) based on differences of resistivity.

2. Materials and methods

2.1. Site description

The study area is located in the Peyne catchment, southern France (Fig. 1) which is characterized by Mediterranean climate. Annual average precipitation is 800–1000 mm and is concentrated in spring and fall. The catchment is situated at the edge of the 'Montagne Noir' and is characterized by a high spatial variation of geological bedrock. Four lithologies were investigated during the ERT experiments: flysch, basalt, marine sandstone, and river terrace sediments (Alabouvette, 1982).

In 2011, we made 12 ERT profiles for 4 sites on four different geological substrates in the beginning and the end of September and the end of October. At each site, we also registered detailed descriptions of soil pits, and obtained gravimetric soil moisture samples. The study area is covered with (semi)natural and agricultural vegetation, mostly vineyards and pasture. The vegetation mainly consists of evergreen shrubs and trees like *Quercus ilex* and *Buxus sempervirens* and is sclerophyll. Three profile sites were chosen in naturally vegetated areas with no recent disturbance and one located in a vineyard-cultivated area.

2.2. ERT

Electrical resistivity tomography (ERT) is a non-invasive geophysical technique for measuring lateral and vertical variation of subsurface electrical resistivity. ERT was selected because, in contrast to most other geophysical methods, like Ground Penetrating Radar (GPR), magnetic susceptibility (MS), gravimetric soil moisture assessment, it provides good information on soil water and can demarcate vertical changes of subsurface soil horizons in the stony soils as found in this region (Nijland et al., 2010; Coulouma et al., 2012). Resistivity measurements are made by inserting an electrical current (I) through two metallic electrodes and measuring the potential difference (ΔV) between two other electrodes (Fig. 2). A single quadruple yields a single value of resistivity, attributed to a single soil volume with dimension and depth defined by the spacing between electrodes and by the configuration used.

Combining measurements of many different electrode combinations along a line allows the calculation of the 2D distribution of electrical resistivity along the transect (Nijland et al., 2010). For 2D ERT surveys, Schlumberger, Wenner and dipole-dipole are the electrode arrays that are the most commonly used. For this study the Schlumberger array was used for its resolving power in both vertical and lateral direction. The measured electrical resistivity of the prospected medium is called apparent resistivity (ρ_a) (Lowrie, 2007):

$$\rho_a = \frac{(AB/2)^2 - (MN/2)^2}{MN} * \frac{\pi \Delta V}{I}$$

where, AB: current electrodes spacing (in m); MN: potential electrodes spacing (in m); ΔV: potential difference (in volts) and I: current (in ampere).

The patterns of resistivity in the soil result from lithology, porosity, structure, temperature, and water content (Lowrie, 2007), all of which differ between regolith and bedrock (Chaplot et al., 2010).

Three geoelectrical measurement campaigns were carried out on four geological substrates. They were performed at the following dates: 5 and 6 September 2011, 21 and 22 September 2011 and 25 and 26 October 2011. In each survey campaign, four 2D electrical resistivity tomography measurements were performed. Data were collected using the Sting R1/IP advanced resistivity meter with one-channel receiver with an array of 28 electrodes with 1 m spacing, which provides reliable resistivity information to a depth of approximately 5.5 m. The electrodes remained in the soil during the whole period of the ERT measurement campaign, also in between periods, to guarantee that measurements were done at exactly the same locations, avoid any electrode polarization changes and to ensure a best quality of measurements (Michot et al., 2003).

Raw ERT data were processed using the EarthImager 2D (Version 2.3.4) software package. EarthImager 2D allows the user to control many different inversion parameters (www.agiusa.com). The inverted resistivity sections were achieved with the EarthImager 2D software. This technique was based on the smoothness-constrained least-squares method and it produced 2-D subsurface model from the apparent resistivity section. In the first iteration, a homogeneous earth model was used as a starting model for which the resistivity partial derivative values could be calculated analytically. For subsequent iterations, a quasi-Newton method was used to estimate the partial derivatives which reduced the computer time. In this method, the Jacobian matrices for a homogeneous earth model were used for the first iteration, and the Jacobian matrices for subsequent iterations were estimated by an updating technique. The model consisted of a rectangular grid. The software determined the resistivity of each mesh which gave a calculated electrical resistivity section according to the field measurements. Then we chose instrument settings which, based on preliminary visual analyses, produced ERT models that best represented physical conditions observed in the soil profiles at our site. After a preliminary inversion of each ERT profile, relative data misfit was checked for all data points in an ERT profile. Individual points with more than 20% misfit were removed. Removal of data points from our profiles was extremely rare, however, which is likely the result of very high quality field data. Misfit histograms typically showed all points in a profile having less than 10% relative data misfit. Inversions were stopped after four iterations or by a Root Mean Square (RMS) error reduction of less than or equal to 1.5%, most inversions reached the inversion criteria on iteration three. Extraction of resistivity profiles from the inversion model is done after all processing and inversion. Due to the nature of these measurements, ERT measures bulk properties (see Fig. 2) and not unique resistivity values at unique locations, the retrieved moisture is an average moisture value for a volume equivalent to the size of the inversion cell.